Available online at www.sciencedirect.com
SciVerse ScienceDirect
Energy Procedia 37 (2013) 7774 – 7782
Energy Procedia

GHGT-11

A roadmap towards a European CO_2 transport infrastructure

Filip Neele[a] *, Tom Mikunda[b], Ad Seebregts[b], Stijn Santen[c], Anton van der Burgt[d], Sarah Stiff[e], Carl Hustad[f]

[a] *TNO, The Netherlands*
[b] *ECN, Amsterdam, The Netherlands*
[c] *CO2-Net, Rotterdam, The Netherlands*
[d] *Stedin, Rotterdam, The Netherlands*
[e] *E.ON New Build and Technology, United Kingdom*
[f] *CO_2-Global, Norway*

Abstract

This paper presents a roadmap for the development of a large-scale CO_2 transport infrastructure in Europe, between 2020 and 2050, which was defined in the EU FP7 CO2Europipe project. The most important conclusions are related to the finding that the EU CCS transport infrastructure is to be led by a relatively small number of countries, who share the largest burden in the areas of CO_2 capture, transport and storage. These include the countries bordering the North Sea, and those countries relying heavily on coal or lignite for their power supply (Germany, Poland the Czech Republic). It is crucial that these countries take the lead and are supported to do so, not only now, but during the whole CCS infrastructure development.

Keywords: CCS road map; CO_2 *transport and storage.*

1. Introduction

It is broadly agreed upon that the increase in anthropogenic greenhouse gases (GHGs) is to a large extent responsible for the increase in global surface temperatures over the past 100 years. Annual emissions of carbon dioxide (CO2), the most important GHG, have grown by approximately 80% between 1970 and 2004. Anthropogenic interference with the climate system is understood, with varying levels of scientific confidence, to result in sea-level rise, increase in the frequency of extreme weather events, threatening ecosystems and decreasing ice sheet coverage [1]. In order to prevent dangerous man-induced climate change, the Intergovernmental Panel on Climate Change estimates that global CO2 emissions need to decrease by between 50% and 85% of their 2000 levels by 2050 [1].

Energy demand is expected to double by 2050 as a result of population growth and economic development. Despite the increasing share of lower CO_2 energy sources (such as renewables and nuclear

doi:10.1016/j.egypro.2013.06.724

power) in the energy mix, significant part of the energy demand will have to be met using fossil fuels such as coal, oil and gas. CO_2 emissions from electricity generation can already be significantly reduced with on average 20 %, by replacing old fossil fuel -fired power plants with state of the art fossil fuel -fired plants. In addition using natural gas instead of coal leads to a further reduction of almost 50 %. Carbon dioxide capture and storage (CCS) is a method to reduce emissions from power plants and industrial processes even further. The costs for developing CCS are high and therefore governmental support or funding is required to develop (demonstration) projects. However, the cost of adaptation to climate change without GHG abatement will be significantly higher [2].

Over the last decade, a number of reports have highlighted CCS as a technology with the potential to make deep emissions reductions [3, 4]. Applications of CCS in the power sector, in particular coal-fired power plants, have been the target of the vast majority of research and development funding and policy initiatives aimed towards demonstrating and commercialising the technology. More recently, research has been conducted to assess the potential application of CCS to various industrial applications such as steel and cement production, and also to oil refining and natural gas processing installations [5].

Currently, most applications of CCS are not economically feasible without fiscal incentives or subsidies, just like any other low carbon technology. The additional equipment used to capture and compress CO_2 also requires significant amounts of energy, which increases the fuel needs of a coal-fired power plant by between 25 and 40% and also drives up the costs [4]. However, it must be noted that although CCS applications will raise the costs of energy generation and industrial production, the IEA has calculated that an exclusion of CCS from the global mitigation portfolio will increase the cost of achieving climate stabilisation by 70% [9]. Based on this information, inclusion of CCS in the portfolio can be justified from a long-term economic efficiency standpoint.

CO_2 is most efficiently transported in dense phase (high density, liquid or otherwise). CO_2 is likely to be transported at high pressures in pipelines made of carbon steel. CO_2 has been transported through pipelines in the United States for use in enhanced oil recovery (EOR) operations since the 1970s, and approximately 3000 km of CO_2 transportation pipeline has been installed. Only small-scale CO_2 carrying vessels exist today and no large-scale CO_2 transport vessels are currently in operation, however such vessels have similar designs to other gas transporting ships such as Liquefied Petroleum Gas (LPG) carriers and thus present no technical challenges for being built. Although few technical barriers to the transportation of CO_2 are foreseen, challenges exist in terms of health and safety standards, operational efficiency, public perception and communication, planning and permitting, CO_2 quality standards and investment and organisation of potential CO_2 transport networks.

At present, major emitters of CO_2 are not given sufficient incentives through market based economic instruments to invest in abatement technology such as CCS. To support the development of CCS in Europe, the European Commission and certain EU Member State governments are providing funding for research and the implementation of demonstration projects. In 2009 the EU announced funding for six demonstration plants throughout Europe, with an aim of commercialising CCS by 2020. Of late, a budget of €1.05 billion has been earmarked, provided by the European Economic Recovery Programme (EERP) [7]. Selected CCS projects can also expect significant co-funding (up to 50%) through the allocation of 300 million emission allowances between in 2011 and 2015 to a fund for innovative renewable and CCS projects [8]. Known as 'NER300' this financing instrument is managed jointly by the European Commission, the European Investment Bank and Member States.

During the demonstration phase of European CCS projects up until 2020, CO_2 transport infrastructure will be restricted to local cost-effective point-to-point pipelines [9]. Depending, on the success of these demonstration projects, post 2020 may see the first large-scale deployment of CCS in the power sector. Developments of clusters are expected to reduce costs, utilise limited space, broaden participation and deepen deployment of CCS [10]. In theory, building pipelines with sufficient capacity to transport CO_2

from multiple sources will lead to lower transportation costs, as investors can take advantage of the economies of scale.

Furthermore, a number of European studies (including CO_2Europipe and GeoCapacity) highlight that if CCS is to support EU CO_2 abatement targets, the absence of sufficient and suitable storage sites in a large number of Member States will require the cross-border transportation of CO_2. In addition, the possibility of conducting CO_2 enhanced oil recovery (EOR) in certain parts of the North Sea may create sizeable demand for CO_2 from multiple EU countries. Therefore cross-border transportation of CO_2 requires multilateral agreements and calls for further EU coordination focusing on harmonising regulatory frameworks.

2. Project objectives

The CO_2Europipe project studied the road toward the long-term, large-scale CO_2 transport infrastructure, drawing conclusions regarding required improvements on the levels of policy, regulations, financing, organisation, risk and technology. Recommendations for EU and national authorities' actions were formulated, which will promote the development of CO_2 transport infrastructure. By doing this, the project aimed to lay out a roadmap towards a future, large-scale transport infrastructure for CO_2. The conclusions and roadmap are based on the requirement for transport and storage, as formulated in an analysis of the development of capture efforts and the availability of storage capacity [11].

The project had the following objectives:

- describe the infrastructure required for large-scale transport of CO_2, including the injection facilities at the storage sites;
- describe the options for re-use of existing infrastructure for the transport of natural gas, that is expected to be slowly phased out in the next few decades;
- provide advice on how to remove any organisational, financial, legal, environmental and societal hurdles to the realisation of large-scale CO_2 infrastructure;
- develop the business case for a series of realistic scenarios, to study both initial CCS projects and their coalescence into larger-scale CCS infrastructure;
- demonstrate, through the development of the aforementioned business cases, the need for international cooperation on CCS;
- summarise all findings in terms of actions to be taken by EU and national governments to facilitate and optimise the development of large-scale, European CCS infrastructure.

3. Large-scale CCS in Europe: vision of long-term transport and storage infrastructure

Maps of CO_2 transport requirements in NW Europe were constructed, using predictions of the increase in CCS projects due to increasingly strict emission reduction targets in the period 2020 – 2050 [11]. Following the end of the (current) demonstration phase, major CO_2 transport and storage infrastructure development is assumed to start from the large-scale introduction of CCS by 2020 and continue until at least 2050. An extensive CO_2 transport infrastructure network will be required if CCS is to play a significant role in achieving the European CO_2 emission reduction goals. Many thousands of kilometres of new high-pressure pipeline will need to be constructed. The main effort in the construction of pipelines would be expected between 2020 and 2030 since the larger part of the network needs to be in place by 2030. The rate of construction may need to be as high as 1200 – 1500 km/yr in some regions. Furthermore, shipping will have a significant role in initial phases until volumes become large enough to justify pipeline investments. The vision for long-term CO_2 transport infrastructure is described in detail elsewhere [11, 12].

Different types of transport infrastructure could develop over Europe, depending on the location and density of capture installations and storage sites. In most areas a network connecting multiple capture locations to several storage sites is expected to emerge.

The distribution of capture efforts, of construction of transport infrastructure and of injection across the Member States reveals that there may emerge a relatively small number of key players. These key players in the development of CCS infrastructure are the countries on the North Sea where the majority of the potential storage capacity resides, whilst additional key players can be identified from their reliance on coal and lignite (e.g., Germany, Poland and the Czech Republic).

During the CO_2Europipe project, a number of concepts and hypotheses have been tested and developed regarding the evolution of a European CO_2 infrastructure. Their outcomes have led to the conclusions described in some detail here. More detail can be found in dedicated reports from the project, referred to in the text below.

4. Recommendations to develop a European CO_2 transport infrastructure

4.1. Political leadership

Given the international character of CCS, it is concluded that strong co-operation is required between Member States, providing clear signals at a pan-European Union level which encourage development to happen. In particular, the planning of CO_2 transport infrastructure and the availability of CO_2 storage sites to projects must be tackled in a manner consistent with the energy needs of Europe over the next few decades. A robust policy roadmap, or equivalent, is fundamentally important for private industry and the public sector alike to efficiently manage the financial and associated risks, and continued leadership at a European level in providing this guiding framework will significantly reduce the uncertainties currently facing potential CCS developments.

Commitment by individual Governments to large-scale deployment of CCS is essential in order for CCS to develop at a pace sufficient to meet EU emission reduction targets. With an uneven spread of the effort in capture, transport and storage across the Member States it is essential that key players in Europe (among which are Germany, Poland, the United Kingdom, Norway and the Netherlands) take the lead. As mentioned above, a clear commitment, at a national as well as a European level, will help develop infrastructure that takes into account future transport and storage demands, including those from neighbouring countries.

4.2. Master plans

One of the ways in which the EU and Member States support the development of CCS and how CCS infrastructure can take shape is through the development and maintenance of Master Plans. These will provide information regarding the timing and size of expected volumes of captured CO_2 together with the planned locations for storage. This will help alignment within industry, focus efforts and improve the efficiency of network development. At the EU level, a CCS Master Plan is recommended to be part of the energy infrastructures plan (which already includes a CO_2 transport network) [13]. At the Member State level, the Master Plans should include cross-border issues and set the timeline for the development of capture efforts and infrastructure construction while also providing relevant information on storage. These Master Plans will provide the EU and Member States with a clear vision on the development of CCS and help disseminate information so that industry may reduce the perceived risk associated with developing CCS projects.

Future emission sources (capture locations) can be assumed to be located at or near current emission points. Suitable storage locations, however, are known with certainty only once storage capacity is proven. Future-proofing transport infrastructure also relies on the early availability of storage capacity. Given the timeline of at least five years for the characterisation and testing of a single storage location, it is of the highest priority that Member States support the qualification of storage locations, to reduce the uncertainty in the location of future injection points. Harmonisation and standardisation of the method of storage qualification (e.g., following the guidelines of DNV CO_2Qualstore) will help decrease the time needed for storage qualification. Particular attention should be paid to qualification of saline formations, which are predicted to take 60-80% of the total amount of CO_2 to be stored, though these currently lack detailed study work.

4.3. Business model for CCS industry: preparing for multi-user networks

The development of CCS clusters is foreseen to start in the period 2020 – 2030, where emission reduction targets cause most European countries to start large-scale capture of CO_2. The clusters are likely to evolve from earlier projects that have resulted in mostly one-on-one systems (i.e. one source - capture site, linked to one sink – storage site). This evolution, however, may require that the organisational models originally developed for point-to-point CCS solutions are reconsidered. This should be understood early in the development of CCS, to enable a smooth transition from early (simple) to later (complex) infrastructure types. A business model is proposed that could attract sufficient capital, providing a sound return on investment [14]. It is recommended that an expert authority is set up, to coordinate cross-border infrastructure investments, to ensure optimum transport capacity utilisation.

4.4. Regulatory certainty and stability

A recurring theme during the analysis of CO_2 infrastructure development has been the need for regulatory certainty, including the compatibility between regulatory regimes of different Member States, and the minimisation of legislative barriers that may impede the rapid development of such infrastructure. The development of European standards and identification of best practices for and relevant to CO_2 transport, where these do not already exist, will also encourage appropriate regulation and create greater certainty. Guidance and recommendations are also being produced specifically for the management of CO_2 in the CCS chain, by several organisations internationally recognised for their health and safety expertise. It is expected that such expert guidance, plus experience from the early CCS demonstration projects will enable appropriate and consistent regulation to be developed.

At least b-lateral co-operation will be essential to ensure that technical solutions to the managed flows of CO_2 are cross-border compatible. This co-operation is also required to ensure that sufficient transport capacity is available to accommodate the increasing CO_2 flows that would occur as a pipeline route traverses industrial regions on its way to a storage area. A central issue is the liability for stored CO_2, which needs to be arranged between Member States. An amendment in 2007 to the 1996 London Protocol allows for the sub-sea storage of CO_2 and its cross-border transport. This will provide the conditions for developing the vast storage capacity in the North Sea. However, the amendment remains to be ratified by most of the Contracting Parties and will not come into force for some time. An interim solution to this problem must be sought by Europe with urgency [15].

The current tendency towards delaying the permitting of onshore CO_2 storage would, if continued, create transport infrastructure biased towards offshore storage locations and hinder countries not bordering the North Sea. The result would be that required onshore pipeline capacity would increase dramatically, with an associated higher cost (increasing from an estimated 50 billion euro to 80 billion euro) and risk. Allowing onshore storage would result in significantly lower overall costs due to shorter transport distances [11, 12].

The development of CCS clusters has great potential for cost sharing and for provision of access to CO_2 infrastructure to both energy and industrial stakeholders. This was demonstrated with economic analyses to conclude that large volumes from different sources lead to lower costs per ton of CO_2 and higher system stability due to smaller throughput variation [14, 16]. Large-scale cross-border CCS in Europe requires amongst others, offshore CO_2 transport and storage in the North Sea with CO_2 from Rotterdam, Groningen Eemshaven and North German harbours.

Recommendations have been formulated in the areas of cross-border transport, third-party access, future-proofing infrastructure through early creation of hubs and interoperability on technical and organisational levels. Last, but not least, the issue of liability for transported and stored CO_2 must be regulated [15, 17].

4.5. Financing CCS infrastructure

The EU-ETS is the mechanism by which the EU may create the financial basis for CCS projects. However, the price of CO_2 emissions is not expected to increase sufficiently rapidly to render CCS commercially feasible. Additional mechanisms should be put in place to support the development of CCS projects after the first wave of demonstration projects [14]. To further increase the attractiveness of CO_2 transport projects for investors, EU coverage for financial guarantees is recommended.

4.6. Commercial opportunities: mutual benefits for CO_2-EOR and CCS

Enhanced oil recovery (EOR) with CO_2 can be an enabler for the development of CCS. The revenues from the additional oil produced can help finance the (early) CO_2 transport infrastructure, with added benefits of additional tax revenues, stability of security of energy supply and greater competitiveness of the EU Member States. The window of opportunity for the application of CO_2-EOR in the major oil fields in the North Sea requires both a rapid and early ramp-up of capture efforts and a concentration of the supply of captured CO_2 towards the oil fields. Early in the development of CCS, an organised, cross-border effort is needed to fully exploit the opportunities of CO_2-EOR [14]. It is recommended to look into the feasibility of aligning CCS development and CO_2-EOR options. A dedicated tax and revenue and burden sharing system could be developed, to render investments in CO_2-EOR projects in the North Sea attractive. Such measures could result in kick-starting both CCS and CO_2-EOR at the same time.

4.7. Safety and risk management: harmonising risk assessment of onshore pipelines

Transport of CO_2 poses health and safety risks. A significant part of the trunk lines will be located onshore. Under certain conditions, leakage or rupture of a pipeline can result in the release of CO_2 with the potential to affect humans and the environment. A number of issues were found that require action for a timely development of the onshore part of the transport infrastructure. It is recommended that risk assessment methods used by Member States are harmonised. A number of knowledge gaps were identified, most of which are being addressed by ongoing research and industrial projects, as well as the planned demonstration projects. In addition to those efforts, it is recommended to collect 'best practices' regarding the safety and risk management of CO_2 pipelines and to set up a database of failure frequencies and experiences [18].

4.8. Technical challenges: closing knowledge gaps

CO_2 pipeline transportation and injection has been standard practice in the United States, where it has evolved during the past 35 years to become a multi-billion dollar industry handling over 30 million tons per year. CO_2 ship transportation is also well known. Knowledge gaps from these processes lie mainly in understanding the effects of impurities in the CO_2 stream on materials in the transport system, and in the operational areas, where injection into depleted gas fields or saline formations and offshore off-loading and injection from a ship are important aspects. These issues can currently be dealt with by implementing slightly more conservative designs, and do not represent barriers to constructing CO_2 transport systems today.

Implementation and scaling of CO_2 pipeline networks in a new arena (e.g. pan-European) and for other CO_2 compositions could reveal new challenges. Optimisation along the whole value chain is essential for decreasing overall costs. The impact of fluctuations in intermittent renewable power supply (reflecting emissions and captured volumes) on the capture process, transport requirements and storage capacity, as well as on the resulting costs should also be considered.

Recommendations at a technical level include the following [17]:

– Conduct additional research to understand the effect of impurities in the CO_2 stream on the behaviour of CO_2 and on the required transport system.
– Data should be collected to validate simulation tools for the behaviour of CO_2 mixtures within the transport and injection system.
– Standards are to be developed for qualification of soft materials in a transport system.
– Concepts are to be developed for depressurisation of transport systems.
– Testing of materials and of ways to prevent the propagation of fractures in a CO_2 pipeline.
– Technology qualification is required for offshore ship offloading systems.

5. Roadmap

The conclusions have been translated in terms of recommendations for actions of the European and Member State Governments, to create the environment that is favourable for the development of CCS [19]. A chronological list of these recommendations is given, which forms a roadmap for the development of CCS, as far as the role of EU and Member State Governments are concerned.

6. Conclusion

Given the international character of CCS, it is concluded that strong co-operation is required between Member States, to provide clear signals at a pan-European Union level which will encourage developments to happen. In particular, the planning of CO_2 transport infrastructure and the availability of CO_2 storage sites to projects must be tackled in a manner consistent with the energy needs of Europe over the next few decades. A robust policy roadmap, or equivalent, is fundamentally important for private industry and the public sector alike to efficiently manage the financial and associated risks, and continued leadership at European level in providing this guiding framework will significantly reduce the uncertainties currently facing potential CCS developments. The key players, which include the North Sea countries and the countries heavily relying on fossil fuels, are to demonstrate commitment in developing CCS.

Clear and internationally consistent Master Plans will help demonstrate Member State commitment. The qualification of storage capacity should be an integral part of the Master Plans; this will provide the necessary certainty of storage to industrial players.

The business model for CCS projects is likely to change as the projects grow and infrastructure coalesces. This process should be understood and supported. For this growth to happen, a stable regulatory playing field is required. Issues that need attention are cross-border transport and liability for transported and stored CO_2 (especially in international networks). Cost-efficient development implies infrastructure sharing, hub development and future-proofing of infrastructure.

The financing of the CCS transport infrastructure must be tackled by implementing mechanisms in addition to the EU-ETS system.

Commercial opportunities for that can help develop CCS transport infrastructure should be utilised whenever possible. CO_2-EOR can be one, when CO_2 from early projects is concentrated towards the North Sea oil fields. This option is to be investigated in detail.

Some technical issues remain to be solved; these include the effect of impurities on the properties of CO_2 and, hence, on the design and performance of transport and storage systems. The development of materials (pipelines able to withstand rupturing), best practices (depressurisation of transport systems for inspection) and systems (offshore ship offloading) is to continue.

Acknowledgements

The CO_2Europipe project has received funding from the European Union's seventh Framework Programme (FP7/2007-2013) under grant agreement no 226317.

References

[1] IPCC. *Summary for Policymakers. Climate Change The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007.

[2] Stern N. *The economics of climate change*, Stern Review, Cabinet office – HM Treasury, ISBN:9780521700801, 2007.

[3] IEA. *Prospects for* CO_2 *capture and storage.* International Energy Agency Publications. Paris, France, 2004.

[4] IPCC. *Special report on carbon dioxide capture and storage*. Metz B, Davidson O, de Coninck HC, Loos M,. Meyer LA (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp, 2005.

[5] UNIDO. *Carbon capture and storage in industrial applications: Technology synthesis report – working paper*, 2010.

[6] IEA. *Energy technology perspectives 2008 – scenarios and strategies to 2050*. IEA/OECD, Paris, 2008.

[7] European Commission. *A European Economic Recovery Plan*. Communication from the Commission to the European Council, Brussels, 2008.

[8] European Commission. *Modalities for co-financing of CCS and innovative renewables demonstration projects under Article 10a paragraph 8 of Directive 2003/87/EC (Emissions Trading Directive) ("NER 300")*. Commission non-paper. Brussels, 2009.

[9] Mckinsey & Company. *Carbon capture and storage: Assessing the economics*, 2008.

[10] Chrysostomidis I, Zakkour P, Bohm M, Beynon E, de Filippo R, Lee A. Assessing issues of financing a CO_2 transportation pipeline infrastructure. *Energy Procedia* 2009; **1**; 1625-1632, 2009.

[11] Neele F, Koenen M, van Deurzen J, Seebregts A, Groenenberg H, Thielemann T. Large-scale CCS transport and storage networks in north-west and central Europe. *Energy Procedia* 2011; **4**; 2740-2747.

[12] CO_2Europipe. *Development of a large-scale* CO_2 *transport infrastructure in Europe: matching captured volumes and storage availability*, CO_2Europipe report D2.2.1, 2011.

[13] http://ec.europa.eu/energy/eepr/doc/com_2012_0445_en.pdf, 2011.

[14] CO_2Europipe. *Development of large scale CCS in The North Sea via Rotterdam as* CO_2*-hub*. CO_2Europipe report D4.1.1, 2011.

[15] CO_2Europipe. *Legal, financial and organizational aspects of* CO_2 *pipeline infrastructures*. CO_2Europipe report D3.3.1, 2011.

[16] CO_2Europipe*Kårstø* CO_2 *Pipeline Project: Extension to a European Case*. CO_2Europipe report D4.3.2, 2011.

[17] CO_2Europipe. *Transport network design and* CO_2 *management*. CO_2Europipe report D3.1.1, 2011.
[18] CO_2Europipe. CO_2 *transport through pipelines: risk characterisation and management*. CO_2Europipe report D3.2.1, 2011.
[19] CO_2Europipe. *Developing a European* CO_2 *transport infrastructure*. CO_2Europipe report D1.1.1, 2011.